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EARTHQUAKE HAZARD MAPPING IN THE MAGHREB COUNTRIES: ALGERIA, MOROCCO, TUNISIA

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SUMMARY

This paper presents new seismic hazard maps of the Maghreb countries by using newly re-evaluated earthquake data catalogue in the region under consideration. For this region, there is a clear need to use common procedure and data bases through the whole Maghreb region so that seismic hazard assessments are consistent from country to country. An effort is made to assess the seismic hazard and to construct earthquake hazard maps in terms of expected horizontal and vertical PGA for a 10 per cent chance of being exceeded, expected intensity (MSK), all in an economic life time of 50 and 100 years. Also, a return period seismic hazard map for PGA $\geqslant 140$ cm/s^2 is presented. For engineering applications, earthquake hazard maps for structures with different periods are also constructed.

KEY WORDS: Maghreb countries; Algeria; Morocco; Tunisia; seismic hazard; mapping

INTRODUCTION

Earthquake hazard problems are encountered mainly in engineering design, city planning, earthquake insurance, land use management and in similar applications. For the Maghreb region countries (Algeria, Morocco and Tunisia), earthquake hazard constitutes a constant threat to human life and property, sometimes causing major economic losses and disruption. The rapid urbanization, development of critical engineering facilities such as nuclear power plants and dams, industrialization of cities with modern types of buildings and the concentration of populations living in hazardous areas are matters of growing concern, as they contribute to heavier loss of human lives and increase considerably the costs of disaster damage.

The first step in reducing the risk of the society from earthquake hazard is an assessment of the hazard itself. Both the seismic hazard analysis and the establishment of seismic hazard maps were made difficult in the Maghreb region by the lack of homogeneous, accurate and complete data. Today, after the re-evaluation of the seismicity of Algeria and adjacent regions during the twentieth century,[1] it became possible to produce these maps. For this purpose, this research work is intended to assess the seismic hazard and to produce earthquake hazard maps in the Maghreb region. An earthquake zoning map for engineering purposes is a map that specifies the levels of the maximum ground motions (forces) for earthquake-resistant design. Seismic hazard maps are practical tools in seismic design of structures because they provide important guidance when it is not feasible to do the earthquake hazard assessment at particular sites. These maps give a good indication on the areal extent of expected strong shaking for large earthquakes.

The findings of this research work should be an integral part of the whole process of economic and social development in Algeria and adjacent regions. They constitute a fundamental means which should guide officials at the national and regional levels in the formulation of development strategies in seismically active

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zones, land use management, revision and enforcement of appropriate building codes and decision-making of policies for preventive measures against earthquake risk affecting the region considered. It is of interest to mention that seismic hazard maps established for engineering application may be different in various ways depending both upon the expected use and the interests of the scientists constructing the maps. For instance, a seismic hazard map for a tall building should be different from one adequate for low-height structures; an earthquake hazard map for nuclear power plant might well be very different from a typical housing unit.

DELIMITATION OF THE ZONE UNDER INVESTIGATION

The zone under investigation, which is defined as the Maghreb, includes Algeria, Morocco, Tunisia and the south Iberian Peninsula, is limited by the latitudes 20°N and 38°N and the longitudes 10°W and 12°E, and shown in Figure 1. The term 'Maghreb' is used to illustrate the extent of the interest of this research work, although Algeria constitutes our main concern. In fact, there are numerous reasons for investigating beyond the boundaries of each country and looking rather into the north African-south Iberian Peninsula region, designated as the Maghreb, as a unit and for assessing the final seismic hazard of the entire zone under similar criteria: (1) *Similar geological process*: the countries limiting the western part of the Mediterranean Sea and its adjacent continuation in the Atlantic Ocean have had, since a hundred million years ago, the same tectonic process marked by a relative motion alternating between left and right lateral along the border of the African and Eurasian plates. (2) *Similar present compressional state of stress*: the actual state of stress in the entire region is dominated by a compression with a principal axis along the NNW–SSE direction. (3) *Similar historical development*: the historical development of the countries in the region shows many common factors, such as cultural background, which lasted for several centuries and are still apparent today. Similarities in population settlements, building stock characteristics and socioeconomic and demographic conditions, etc.,

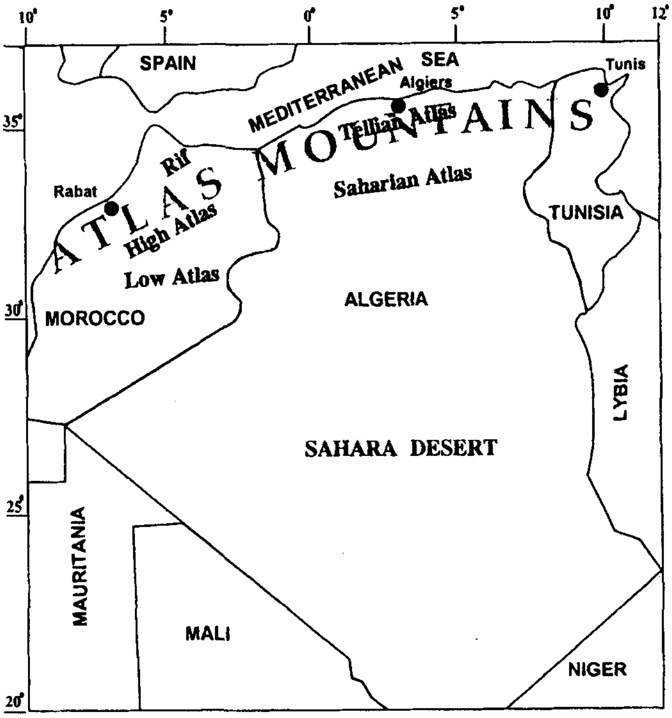

Figure 1. Map showing the limits of the Maghreb region

are very important parameters in the whole process of seismic hazard studies in the region. The selection of this area allows investigation of any earthquake, affecting although not necessarily occurring in a specific zone of the Maghreb region, which may influence the seismic hazard assessment in any particular zone of the region under survey. The term 'Atlas' is used to define the block containing the Atlas Mountains along the whole of North Africa (Figure 1).

SEISMIC HAZARD ANALYSIS METHODOLOGY

Numerous methods for earthquake hazard assessment in a given site are available today. In 1966, Lomnitz and Epstein[2] employed the Poisson process for the occurrence of large earthquakes which is still used. In 1968, Cornell,[3] Esteva[4] and Milne and Davenport[5] derived the general basis for the most complete analysis of the whole seismic hazard problem with the inclusion of the propagation mechanism of the ground motion. In 1972, Shah and Vagliente[6] used the Markov model of earthquake prediction in seismic hazard analysis. A methodology for seismic hazard estimation based on historical earthquake occurrences is presented in detail in Tomatsu and Katayama[7] and Molas and Yamazaki.[8,9]

Summary of analysis method

The seismic hazard evaluation at a specified site depends upon the definition of the following four conditions:

(a) *An earthquake source model.* It is based on geological evidence, seismic sources are identified and modelled as a line, area or dipping plane. In this study, an annular source model is used.

(b) *A seismicity model.* The seismicity of each of the modelled sources is first determined from past data available. The recurrence relationship relating the size of the past events in terms of Peak Ground Acceleration (PGA) is derived. The seismicity model used in Tomatsu and Katayama[7] and Molas and Yamazaki[8,9] is usually taken as

$$\log(\mu) = a - b\log(y) \tag{1}$$

where y is the peak ground acceleration, μ is its occurrence rate and a and b are regression constants. This relation can be written as

$$\log(y) = (\log(T) - a)/b \tag{2}$$

where $T\ (= 1/\mu)$ is the return period of T yr. Thus, equation (2) represents the peak ground acceleration with a return period of T yr.

(c) *An attenuation model of ground motion information.* This describes the transfer of ground motions from the source to a particular site as a function of magnitude, distance and soil conditions. Here, the peak ground acceleration is used to characterize the ground motion; the attenuation law is in the form

$$\log(y) = b_1 + b_2(\mathrm{Ms}) - b_3\log(r) - b_4(r) \tag{3}$$

where $r^2 = d^2 + h^2$, r is the hypocentral distance, d is the epicentral distance, h is the focal depth, y is the peak ground acceleration, and Ms is the surface-wave magnitude. This attenuation law is required to determine the regression constants a and b. Then, a linear regression fitting is carried out at each given site within the region under consideration.

(d) *A recurrence forecasting model.* Various statistical models have been tested in research papers; however, for practical purposes, earthquakes are considered to be random events, and the Poisson process is used, which implies assumptions of stability and independence over time. Since hazard analysis defines the occurrence of ground motions equal to or larger than a specified value, the probability of exceedance is used. For a Poisson process this may be expressed as

$$p = 1 - \exp(-\mu t) \tag{4}$$

where μ is the mean annual occurrence rate of events of particular peak ground acceleration over a given time t. From equations (1) and (3), the value of the peak ground acceleration for a given p and time period t is then calculated as

$$\log(y) = \log(-\ln(p/t) - a)/b \tag{5}$$

From the assumption of the Poisson process, the relation between the probability of exceedance and the return period of peak ground acceleration, T, is given by

$$T = 1/\mu = -t/\log(p) \tag{6}$$

Earthquake source data

As with any quantitative analysis, the input data toward a seismic hazard analysis are critical. It is, however, clear that the results of any study based mainly on an inventory of data available from different sources is subject to the quality and completeness of the information. Thus, the earthquake data available today will determine the accuracy of this research work and the significance of the conclusions drawn.

The newly compiled earthquake catalogue for the Maghreb region during the period[10] 1900–1990 is used in this research work. This catalogue is as homogeneous, complete and accurate as the available macroseismic and instrumental data allow. The earthquake data set used in this work has been re-evaluated[11] with a consistent process and is considered to be reliable in both homogeneity and completeness. It is of interest to mention that the seismicity of the Maghreb region goes back well before 1900; nevertheless this seismicity (pre-1900) is not yet revised and its data are still non-homogeneous and thus not included in the analysis.

Because the Atlas region is in a collision zone, earthquakes occur generally at small depths. The focal depth remains the most uncertain of hypocentral co-ordinates; its estimation from teleseismic data alone is not precise enough to determine small differences in focal depths of less than 10 km. In the Maghreb region, more than 70 per cent of the earthquakes with focal depths available are found to have occurred at less than 15 km. In this study, a focal depth of 10 km is assumed for all earthquakes with unknown focal depths. Earthquakes with focal depths greater than 100 km are excluded from the analysis.

This catalogue was analysed for completeness using the method proposed by Stepp.[12] This method determines the time period in which the estimate of the occurrence rate of a certain magnitude class is stable. The Maghreb earthquake catalogue was found to be complete for Ms $\geqslant$ 3·0 from 1961; Ms $\geqslant$ 3·6, from 1956; Ms $\geqslant$ 4·2, from 1921 and for Ms $\geqslant$ 4·8, from 1900. The geographical distribution of epicentres of this earthquake catalogue is shown in Figure 2.

Due to the lack of a seismotectonic map, there is a significant uncertainty on long-term rates of earthquakes and on individual faults based on trenching studies, etc.; the twentieth century seismicity in general provides the best available earthquake data for assessing seismic hazard in the Maghreb countries. This means that in evaluating seismic hazard at any site we can do no better today than to assume that future earthquakes will tend to take place very close to past seismic events, i.e. to estimate seismic hazard based on historical earthquake occurrence around the site.

It is of interest to mention that to establish the occurrence rates of the peak ground acceleration, only the earthquakes whose magnitudes are within the class of completeness for the specific period are used. In order to homogenize the earthquake data sample, correction factors are applied to the occurrence rates based on the magnitude's time period of complete reporting. If y_i is the largest peak ground acceleration equal at the site, then the occurrence rate, μ_i, can be determined as

$$\mu_i(Y > y_i) = N/t \tag{7}$$

where N is the number of peak ground accelerations equal to or greater than y_i and t is the time period of the observation.

Let n_k be the number of occurrences for $Y = y_k$ for all y_k's $> y_i$. Then equation (7) can be rewritten as

$$\mu_i(Y > y_i) = \sum n_k/t \tag{8}$$

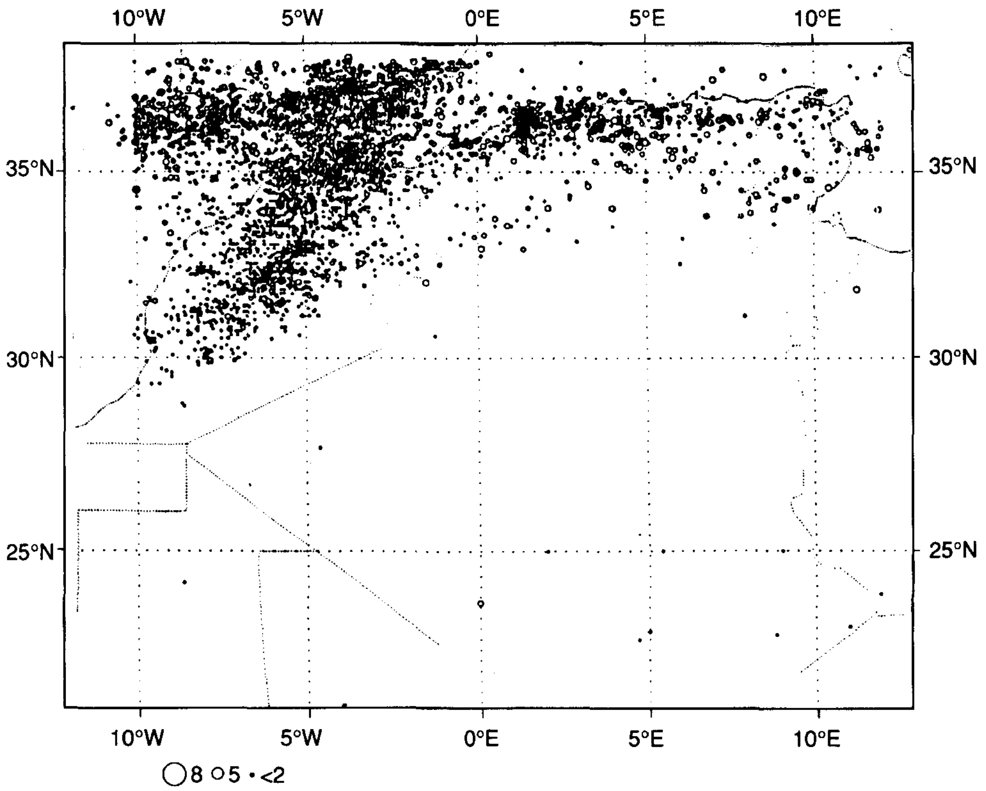

Figure 2. The geographical distribution of the seismicity of the Maghreb region during the twentieth century (including foreshocks and aftershocks).

let t_r be a reference time period, and t may change for each level of magnitude. Then,

$$\mu_i(Y > y_i) = \sum (n_k \cdot t_r/t_k)/t_r \tag{9}$$

where t_r/t_k is a correction factor applied to the number of occurrences of the peak ground motion for earthquakes not belonging to the reference time period. In this research work, the longest time period was used as the reference. For seismic events with Ms $\leqslant$ 4·8, a correction factor of 91/70 or 1·3 is applied, and for Ms $\geqslant$ 4·8 the catalogue is found complete; therefore the correction factor is equal to unity. This methodology allows the use of data selected from different time periods in the regression analysis.[8,9].

Attenuation law of peak ground acceleration

The quantitative assessment of seismic hazard at any particular site within a region requires an attenuation law for the Peak Ground Acceleration (PGA). The maximum ground motion to be expected in the site constitutes a crucial problem in earthquake engineering. For the Maghreb region, as in many other parts of the world, no PGA attenuation law has been developed, due mainly to the shortage of strong motion data. However, in order to assess the seismic hazard in this region, we have to adopt an attenuation law from the literature. A great amount of PGA attenuation relationships, predicting strong ground motions in terms of magnitudes, distance, site geology, and in some cases other factors, using various models and data sets are established for different parts of the world. Reviews of these laws are presented in Idriss,[13] Boore and Joyner,[14] Campbell[15] and Joyner and Boore.[16] Examples include the attenuation laws derived by Molas and Yamazaki[17] for Japan, which is presented in equation (10), and that by Ambraseys[18] for Europe, which includes strong ground motion data of Algeria, for which the horizontal component is shown in equation

(11). Ambraseys[18] also derived a PGA attenuation for vertical component which is also used in this work to produce earthquake hazard maps based on vertical acceleration in the Maghreb countries, and is presented in equation (12).

(1) *Mean Molas and Yamazaki*[17] *PGA attenuation relation*

$$\mathrm{Log}(y) = 0{\cdot}206 + 0{\cdot}477\, M_j - \log(R) - 0{\cdot}00144(R) + 0{\cdot}00311(h) \tag{10}$$

where M_j is the JMA magnitude ($M_j = (1{\cdot}82 + \mathrm{Ms})/1{\cdot}27$), h is the depth (km), R is the closest distance to the fault rupture (km) and y is the PGA (cm/s^2).

(2) *Mean Ambraseys*[18] *PGA attenuation relations*

(a) *Horizontal acceleration*

$$\log(y_h) = -1{\cdot}43 + 0{\cdot}245(\mathrm{Ms}) - 0{\cdot}0010(R) - 0{\cdot}786 \log(R) \tag{11}$$

with $R = (D^2 + (2{\cdot}7)^2)^{1/2}$

(b) *Vertical acceleration*

$$\log(y_v) = -1{\cdot}72 + 0{\cdot}243(\mathrm{Ms}) - 0{\cdot}00174(R) - 0{\cdot}750 \log(R) \tag{12}$$

with $R = (D^2 + (1{\cdot}9)^2)^{1/2}$

where y_h and y_v are respectively the horizontal and vertical PGA (g), R is the focal distance (km), and D is the epicentral distance (km).

The former is based on data set of 2166 pairs of orthogonal horizontal components from 387 seismic events, of which depth varies up to 200 km, recorded at 76 JMA stations, and the latter has been derived from 1667 accelerograms recorded mainly on soft rock or soil from 865 seismic events of all depths mainly in the European, Middle East and Mediterranean regions, which include the Algerian data.

These two attenuation laws are chosen to conduct the seismic hazard analysis in the Maghreb countries because the Molas and Yamazaki[17] relation is derived for shallow and deep earthquakes and to show the influence of attenuation laws on seismic hazard evaluation; that of Ambraseys[18] is also developed for all depths and with data of the Mediterranean region including Algerian data.

Attenuation of acceleration response spectrum

The response spectrum is the best representation of ground motion because it gives the possibility to take into account the natural period of the structure. It constitutes the basis of most seismic-resistant design and defines the relation between the period of the structure considered and the lateral forces. The response spectrum is of great interest for engineering purposes because it represents the maximum response, to the given motion, of a sample of single-degree-of-freedom models of structures. Also, the spectral attenuation of ground motion allows to assess a structure's natural period-dependent seismic hazard at any site and thus period-dependent seismic zoning.

Several authors have developed spectral attenuation laws which are reviewed in Joyner and Boore.[16] Molas and Yamazaki[19] developed two different models to predict the acceleration of response spectra based on magnitude, distance and site conditions. Examples used in this study are Molas and Yamazaki[19] spectral attenuation laws, which are given in respect of the structure natural undamped period and a 5 per cent damping ratio are used to produce an earthquake hazard map based on the structure's period in the Maghreb countries.

Attenuation of intensity

Despite the increase in numbers of strong motion accelerographs, intensity continues to be a necessary measure of the size of ground shaking in earthquakes. When assessed consistently for a large enough number

of earthquakes, to represent the seismicity of a given region, the intensity may reveal regular isoseismal models which can be taken as a simple radiation pattern associated with a point source. This approach remains very practical for an efficient estimation of the interaction between environment and earthquakes, and thus seismic hazard and risk. For some parts of the world, the intensity may constitute a better correlation with damage than peak ground acceleration alone. Seismic hazard studies based on intensity have been made by numerous scientists (e.g. Cornell[3]). Benouar[20] derived an intensity-attenuation law for the Atlas block. This attenuation relationship for MSK intensity and distance in the Atlas block is estimated by using an earthquake sample set which consists of 123 (Ii, Di) pairs corresponding to 32 seismic events, where Ii is the intensity (MSK) corresponding to the mean radius Di. The Benouar[20] mean intensity attenuation expression for the Atlas block is

$$I = 5{\cdot}16 + 1{\cdot}48\,(\mathrm{Ms}) - 0{\cdot}00074\,(R) - 4{\cdot}73\log(R) \tag{13}$$

where $R = [D^2 + (4{\cdot}82)^2]^{1/2}$, I is the intensity (MSK),Ms is the surface-wave magnitude, R is the focal distance (km) and D is the epicentral distance (km).

This expression is used to produce seismic zoning maps based on intensity in the Maghreb countries.

RESULTS OF EARTHQUAKE HAZARD MAPPING

Earthquake hazard mapping is a fundamental step toward reduction of seismic risk. An earthquake hazard map for engineering use in a map that specifies the level of loads for earthquake-resistant design. It is the basis for introducing low-cost earthquake-resistant building design and construction as well as for land use planning and siting new critical engineering facilities such as nuclear power plants and dams. They constitute continuous working documents, provisional judgements on future earthquake activity.

Methodology

In order to estimate the seismic hazard within a given region with a certain degree of reliability, the whole region is subdivided into a large enough number of grids of which the intersections constitute the sites where the selected seismic hazard parameters (e.g. PGA, Intensity, Return Period) are calculated. Then contour lines are drawn, linking all different sites with equal seismic hazard. This contour lines map is known as an earthquake hazard map for the region considered.

Selection of earthquakes around the site

To estimate the seismic hazard in any particular site within a region requires a selection of earthquakes which affect significantly the value of the hazard output. However, there is no strict rule for selecting the maximum epicentral distance to the site. A sensitive study for different maximum epicentral distances, for five sites in the region considered, was carried out to show the influence on the seismic hazard evaluation at two sites in the Maghreb region. A small area around the site results in a smaller number of earthquakes to be considered and some events outside the zone considered may affect the hazard in the site. This, naturally, will decrease the data set for regression. On the other hand, a too large area may include earthquakes which do not affect the seismic hazard in the site and are thus useless. The findings show that for an epicentral distance of 200 km and beyond, the b-coefficient of the Gutenberg–Richter formula is relatively stable. Thus, it is assumed that significantly earthquakes are equally likely to occur anywhere in the area of 200 km in radius surrounding the site under consideration. The source zone is assumed to be at a depth of 10 km which is based on the focal depth of most earthquakes in the Maghreb region.[1]

Regression analysis

In applying the linear regression to each site which is taken as the centre of an area of 200 km radius and where past earthquakes are likely to occur again, it was found that very high peak ground accelerations are

calculated in some very low seismicity zones. For the Maghreb countries, the seismicity is rather diffuse and consists of a large number of shallow earthquakes with relatively moderate to small magnitudes.[10] It was found that the fitting curve of peak ground acceleration and its occurrence rate do not fit the data adequately. This is due to the high mean annual occurrence rates of small peak ground acceleration. To solve this problem, we studied 20 sites where unusually high values of the PGA are found and also some other random sites were also analysed. Figure 3 shows the regression curve fitting for a site where high PGA was calculated. It can be clearly seen that taking into account so many small accelerations tend to flatten the regression line and thus affect seriously the earthquake hazard in the site.

The findings of this study suggest that these small events be removed from the analysis by cutting the regression at $\mu = 1$ (i.e. disregarding data with occurrence rates greater than 1·0 per year) be applied to the evaluation of seismic hazard in the Maghreb countries. A good fit of the new regression line with the data sample with a cut-off at $\mu = 1$ is shown in Figure 3. Obviously, cutting the data sample for these sites will tend to decrease the value of the predicted PGA. This will be more visible if only a small number of high PGA occurred at the site.

The evaluation of seismic hazard at a site is carried out only if the number of earthquakes in the area considered (200 km radius) is larger than 10 and the surface-wave magnitude is equal to or greater than 4·0.

Regional seismic hazard

The computation of the seismic hazard in the Maghreb countries has been carried out using the H-Map computer program developed by Molas and Yamazaki[8,9] at the Institute of Industrial Science, University of Tokyo. The earthquake data for the Maghreb region has been prepared by Naili Mounir, a post-graduate student at the Civil Engineering Institute of the University of Algiers (USTHB, Algeria).

The Maghreb region, as defined in Figure 1, has been first divided into ninety-nine grids having sides of two degrees. These grids have been in their turn divided into 441 grids with sides of 0·1 degree which

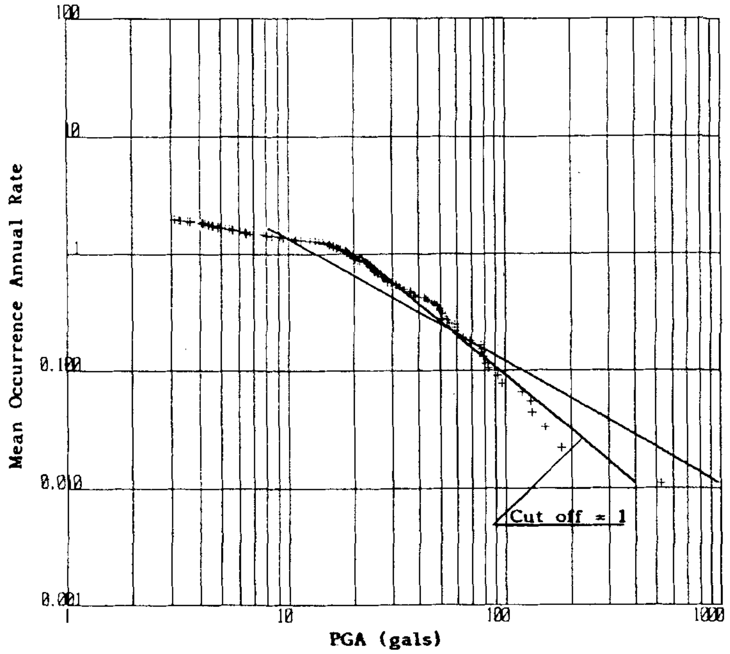

Figure 3. The plot of the peak ground acceleration versus the mean annual occurrence rate for the site located at 1·40°E and 36°·10N

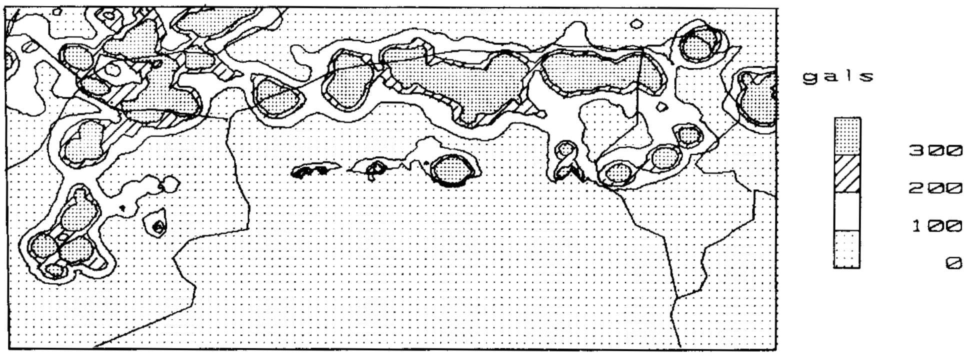

Figure 4. The geographical distribution of the expected peak ground acceleration for a 10 per cent probability of exceedance in an economic life of 100 yr using Ambraseys[18] horizontal-PGA attenuation law

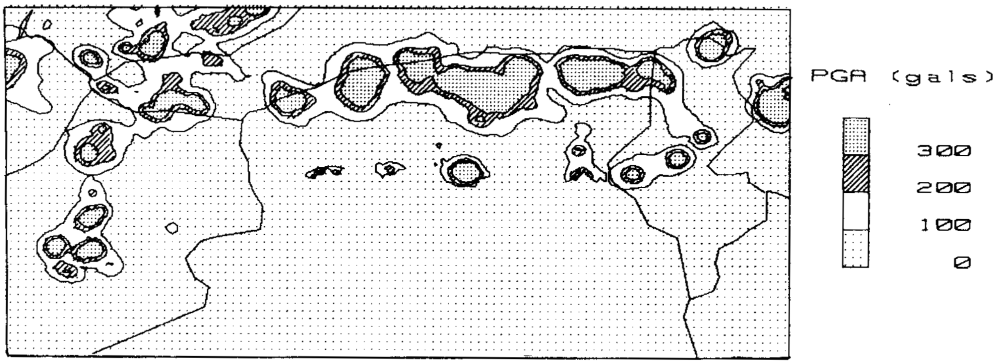

Figure 5. The geographical distribution of the expected peak ground acceleration for a 10 per cent probability of exceedance in an economic life of 100 yr using Molas and Yamazaki[17] horizontal-PGA attenuation law

constitutes 46 659 grid points and for which seismic hazard has been estimated. This means that seismic hazard has been calculated in about every 10 km distance which could illustrate the trend of seismic hazard with a certain degree of reliability.

Earthquake hazard maps

Earthquake hazard in the Maghreb countries is estimated in terms of (1) expected peak ground horizontal and vertical accelerations for a 10 per cent probability of exceedance, (2) expected structure's period-dependent spectral amplitudes for a 10 per cent probability of exceedance, (3) intensity (MSK) all in an economic lifetime of 50 and 100 yr and (4) return period in years for PGA $\geqslant$ 140 cm/s^2 which is considered as an important value in engineering purposes.

Due to space limitations, only the following maps are presented for scientific purposes to illustrate the seismic hazard in the Maghreb countries:

Figure 4 shows the geographical distribution of the expected peak ground acceleration for a 10 per cent probability of exceedance in an economic life of 100 yr using Ambraseys'[18] horizontal attenuation law. Figure 5 shows the geographical distribution of the expected peak ground acceleration for a 10 per cent probability of exceedance in an economic life of 100 yr using Molas and Yamazaki's[17] horizontal attenuation law. The Molas and Yamazaki[17] attenuation law gives generally values very close to those of Ambraseys,[18] except when the PGA value is more than 980 gals; then the values of Molas and Yamazaki[17] are lower by about 200 gals. These two attenuation laws tend to show the same high seismic hazard zones which clearly

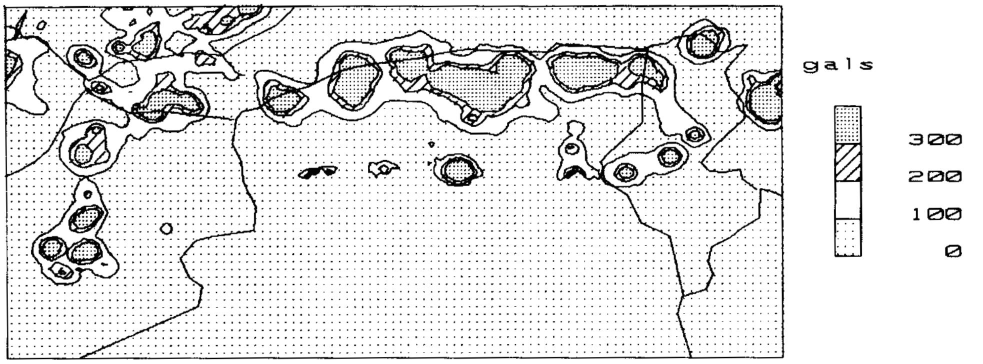

Figure 6. The geographical distribution of the expected peak ground acceleration for a 10 per cent probability of exceedance in an economic life of 100 yr using Ambraseys[18] vertical-PGA attenuation law

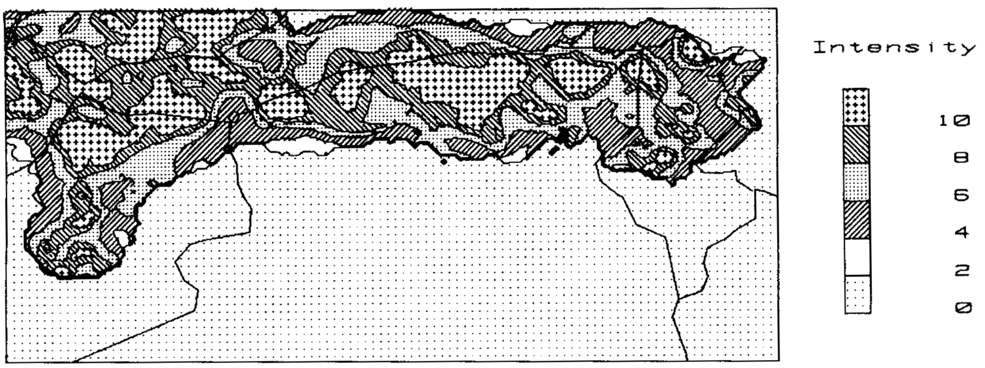

Figure 7. The spatial distribution of seismic hazard, in the Maghreb countries, in terms of intensity (MSK), for an economic life time of 100 yr using Benouar[20] intensity-attenuation law

correspond to the earthquake seismic source zones. In Algeria, the highest seismic hazards are found to be in the regions which were struck by several damaging earthquakes during this century which are El-Asnam, Setif and Constantine regions in central western, central eastern and eastern Algeria respectively. The zone limiting the Tell Atlas and the Sahara Atlas shows a certain seismic stability. The Sahara desert is an earthquake free zone; it is of interest to mention that very few earthquakes were reported and no seismic lineament can be clearly observed. This is in complete agreement with the seismicity map of the Maghreb region (Figure 2).

In examining the western part of the Maghreb region which includes Morocco and the southern Iberic peninsula, it may be easily seen that the highest seismic hazard is found in the Rif and High Atlas which are the western branch of the Algerian Atlas mountains. In Tunisia, there is a seismic north and an aseismic south. The zone north of 34°N presents a higher earthquake hazard.

The highest seismic hazard is concentrated within the coastal band of about 200 km wide along the border on the African tectonic plate which is in collision with the Eurasian plate. This clearly follows the Atlas mountains block from Agadir (Morocco) to Tunis (Tunisia) which experiences periodically low to moderate earthquakes.

Figure 6 shows the geographical distribution of the expected peak ground acceleration for a 10 per cent probability of exceedance in an economic life of 100 yr using Ambraseys[18] vertical attenuation law. This figure shows a significant seismic hazard due to the vertical acceleration component which constitutes one of

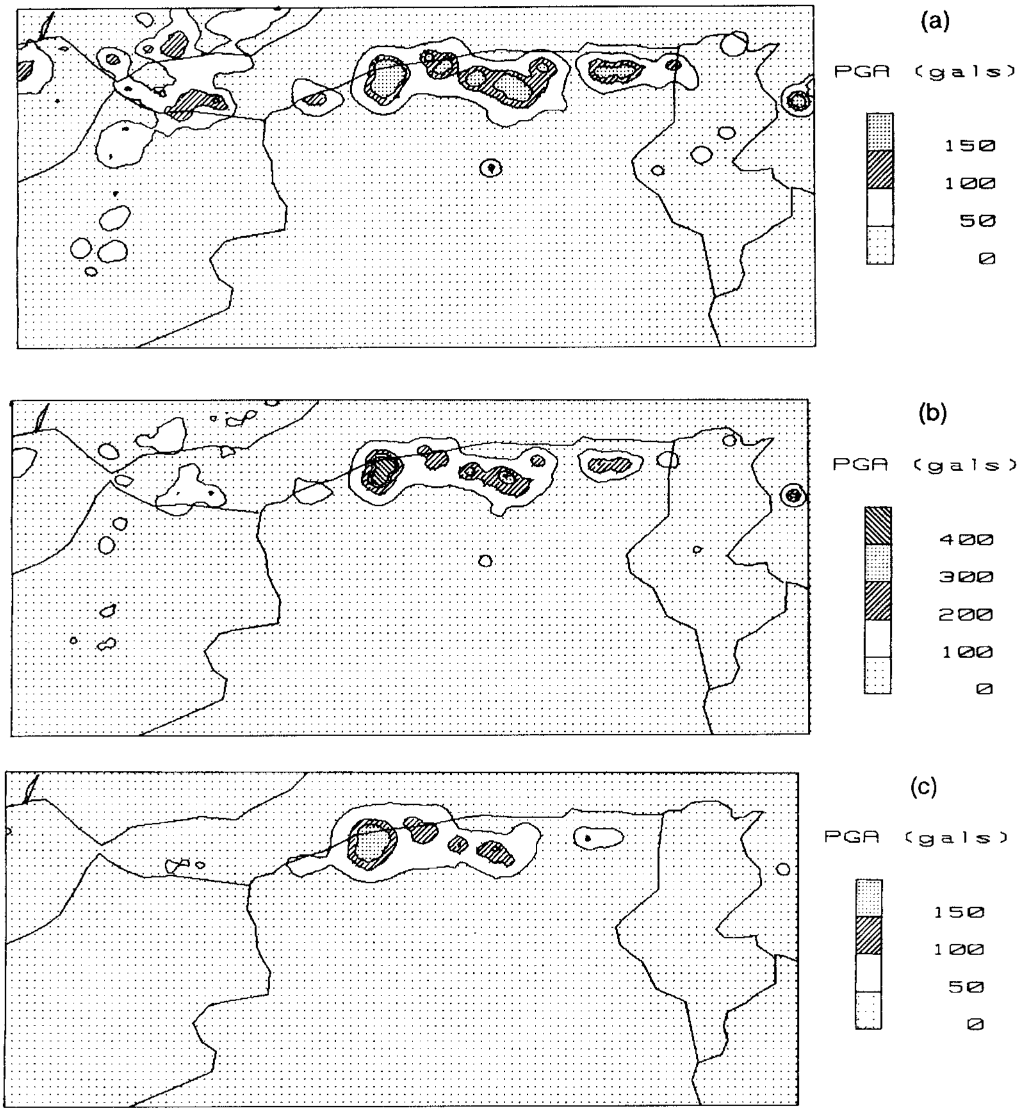

Figure 8. The distribution of expected structure's period-dependent spectral absolute amplitude (gals) for periods of (a) $T = 0{\cdot}1$ s; (b) $T = 0{\cdot}3$ s; (c) $T = 1$ s; using Molas and Yamazaki's[19] spectral attenuation law

the main causes of damage in several past Algerian earthquakes. The same seismic hazard trend, as for the horizontal component, can be easily observed.

Figure 7 shows the spatial distribution of seismic hazard, in the Maghreb countries, in terms of intensity (MSK), using Benouar[20] intensity-attenuation law for an economic life time of 100 yr. The same seismic hazard trend appears as in maps constructed from PGA attenuation laws.

Figure 8 show the expected structure's period-dependent spectral absolute amplitude (gals) for periods of (a) $T = 0{\cdot}1$ s, (b) $T = 0{\cdot}3$ s and (c) $T = 1$ s using Molas and Yamazaki[19] spectral attenuation law. These maps show a high seismic hazard for these types of structures in central eastern Algeria.

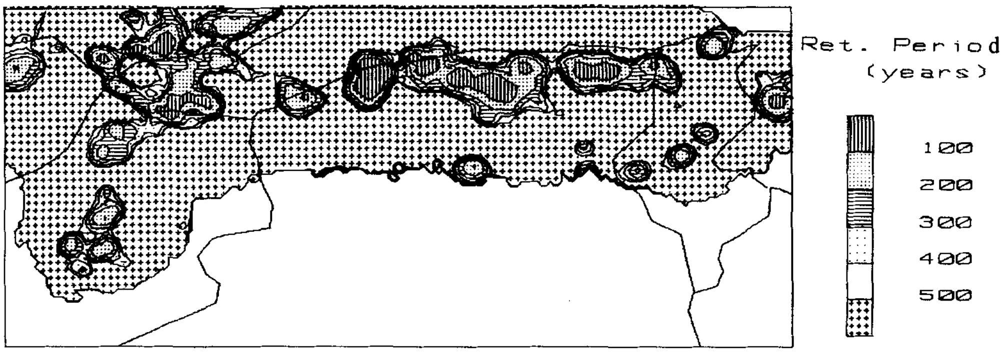

Figure 9. The spatial distribution of seismic hazard assessment in the Maghreb countries in terms of return period in years for PGA $\geqslant$140 gals using Ambraseys[18] horizontal-PGA attenuation law

Figure 9 shows a seismic hazard assessment in the Maghreb countries in terms of return period in years for PGA $\geqslant$ 140 gals, using Ambraseys[18] PGA attenuation law. It can be easily seen that higher seismic hazard is observed in El-Asnam zone.

CONCLUSIONS AND RECOMMENDATIONS

The new Maghreb countries seismic hazard maps are constructed in terms of expected peak ground accelerations and MSK intensities for a 10 per cent probability of exceedance, expected spectral amplitudes (gals) for 5 per cent damping and different structural periods, return period in years for PGA $\geqslant$ 140 gals which should be of great use in the social and economic development strategies in the Maghreb countries.

It is of interest to mention that every 10 to 15 yr, while more data on earthquakes are accumulated and seismological understanding improved, these maps should be renewed. However, seismic hazard maps are also modified whenever a large earthquake occurs in the region considered. But, we should keep in mind that a good seismic zoning map should not be dependent on individual past earthquakes. This may be achieved when the catalogue is complete and the time span of the historical seismicity is long enough to include seismic events with large return periods.

Due to the lack of a seismotectonic map in the region under consideration, in order to make a probabilistic (source based) hazard analysis we used a catalogue-based earthquake hazard mapping. This scenario is very common for many developing countries and this methodology will benefit many who are most affected by earthquake disasters.

These seismic hazard maps are addressed to a broad range of users, including high-level government officials, administrators, civil engineers, architects, earth scientists, seismologists, planners, technical experts and researchers in all these disciplines. They should constitute an integral part of the whole process of economic and social development in the Maghreb countries — Algeria, Morocco, Tunisia. They provide a fundamental means which should guide officials at the national and regional levels in the formulation of development strategies in seismically active zones, land use planning, development or revision of building seismic design code, reinforcement of existing buildings, improving construction methods and materials as well as decision-making of policies for preventive measures against earthquake risk affecting the zone considered. The findings of this research work, coupled with vulnerability studies, must guide, stimulate and facilitate the efforts of the respective governments, the earthquake engineering and the disaster mitigation planning communities to take specific practical preventive measures to reduce earthquake risk.

From this study, it can be concluded that the seismic design level in the Algerian seismic design code (RPA 88)[21] is considerably low. Therefore, the Algerian building seismic design code must be revised according to the newly constructed seismic hazard maps. The Moroccan seismic building design and construction code (RPS 82)[22] is in good agreement with the results of this work. We believe that Tunisia should develop and implement a seismic building code using the earthquake hazard maps produced in this research. In reality introducing new construction materials and procedures without an adequate seismic building code and the rigorous implementation of its regulations may only produce new types of vulnerable structures.

This research work leads to more complete knowledge about of the distribution of seismic hazard in the Maghreb countries and will improve the methods for assessing the likelihood, scope and severity of impact and losses in future earthquake disasters.

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REFERENCES

1. D. Benouar, 'Materials for the investigation of the seismicity of Algeria and adjacent regions during the twentieth century', *Special Issue of Annali Di Geofisica*, **XXXVII**, 459–860 (July 1994).
2. C. Lomnitz and B. Epstein, 'A model for occurrences of large earthquakes', *Nature* **211**, 954–956 (1966).
3. C. A. Cornell, 'Engineering seismic risk analysis', *Bull. seism. soc. Am.* **58**, 1583–1606 (1968).
4. L. Esteva, 'Bases para la formulacion de decisiones de diseno sismico', Instituto de Inginiera, No. 182, Universidad Nacional Autonoma de Mexico, 1968.
5. A. Milne and A. G. Davenport, 'Distribution of seismic risk in Canada', *Bull. seism. soc. Am.* **59**, 729–754 (1969).
6. H. C. Shah and V. N. Vagliente, 'Forecasting the risk inherent in earthquake resistant design', in *Proc. int. conf. on microzonation*, Vol. 2, 1972.
7. Y. Tomatsu and T. Katayama, 'An online graphic computer program [ERISA-G] and its application to seismic macrozonation of Japan', *Proc. 9th world conf. on earthquake eng.*, Tokyo-Kyoto, Japan, Vol. 2, pp. 181–186, 1988.
8. G. L. Molas and F. Yamazaki, 'Seismic hazard analysis in the Philippines using earthquake occurrence data', *Proc. 10th world conf. on earthquake eng.*, Madrid, Spain, pp. 6031–6036, 1992.
9. G. L. Molas and F. Yamazaki, 'Seismic macrozonation of the Philippines based on seismic hazard analysis', *Structural eng. earthquake eng.* **2**(1), 33–43, 1994.
10. D. Benouar, 'An earthquake catalogue for the Maghreb region [20°–38°N, 10°W–12°E] during the twentieth century', (the Office des Publications Universitaires, Algeria, 1994, in press).
11. D. Benouar, 'The seismicity of Algeria and adjacent regions during the twentieth century', *Ph.D Thesis*, Civil Engineering Department, Imperial College, University of London, 1993.
12. J. C. Stepp, 'An investigation of earthquake risk in the Puget sound area by use of the type I distribution of large extremes, *Ph.D Thesis*, Pennsylvania State University, State College, PA, 1971.
13. I. M. Idriss, 'Characteristics of earthquake ground motions, in earthquake engineering and soil dynamics', *Proc. Am. Soc. Eng. Geotech. Eng. div. specialty Conf.*, Pasadena, CA, Vol. 3, pp. 1151–1265, 1978.
14. D. W. Boore and W. B. Joyner, 'The empirical prediction of ground motion', *Bull. seism. soc. Am.* **72**, S43–S60 (1982).
15. K. W. Campbell, 'Strong motion attenuation relations: a ten-year perspective', *Earthquake spectra* **1**, 759–804 (1985).
16. W. B. Joyner and D. W. Boore, 'Measurement, characterization and prediction of strong ground motion', in *Proc. ASCE conf. earthquake eng. soil dyn.*, Park City, Utah, pp. 43–102, 1988.
17. G. L. Molas and F. Yamazaki, 'Attenuation of earthquake ground motion in Japan including deep focus events', *Bull. seism. soc. Am.* **85**, 1343–1358 (1995).
18. N. N. Ambraseys, 'The prediction of earthquake peak ground acceleration in Europe', *Earthquake eng. struct. dyn.* **24**, 467–490 (1995).
19. G. L. Molas and F. Yamazaki, 'The effect of source depth and local site to the attenuation characteristics of response spectra', *Proc. 23rd JSCE earthq. eng. symp.*, pp. 69–72, 1995.

20. D. Benouar, 'Magnitude-intensity and intensity-attenuation relationships in the Atlas zone and Algerian earthquakes', *Earthquake eng. struct. dyn.* **23**, 717–727 (1994).
21. RPA 88, 'DTR B-C 2-48: Règles Parasismiques Algériennes', Document technique règlementaire, Ministère de l'Urbanisme et de la Construction, Alger, Algeria, 1988.
22. RPS, 'Règles Parasismiques Marocaines', Ministry of Construction, Rabat, Morocco, 1982.